POWER BALANCE IN STELLARATOR REACTORS

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Abstract:

The Helias stellarator reactor is an upgrade version of the Wendelstein 7-X device taking into account the design criteria of a power reactor. The dimensions of a Helias reactor are: Major radius 22 m, average plasma radius 1.8 m, magnetic field on axis 4.75 T, fusion power about 3000 MW. Neoclassical transport sets a lower limit on plasma confinement, and extensive numerical calculations have been done to clarify this issue. Extrapolating empirical scaling laws to a Helias reactor shows that anomalous confinement determines the ignition conditions. The effect of parameter variations on ignition is studied. The result of these zero dimensional calculations is also compared with start-up scenarios obtained with the ASTRA code.

1. INTRODUCTION

The Helias reactor is an upgraded version of the Wendelstein 7-X experiment under construction in Greifswald. The dimensions of a Helias reactor are determined by the following requirements.

- There must be sufficient space for blanket and shield
- The magnetic field is small enough to allow for NbTi-superconducting coils
- Plasma confinement must be sufficiently good to provide ignition.

The main data of the Helias reactor are listed in the following table

Table 1: Basic data of Helias reactors

Device		HSR22A	HSR22B	HSR22C
Major Radius	R [m]	22	22	22
Minor Radius	a [m]	1.8	1.8	1.8
Plasma Volume	V [m^3]	1407	1407	1407
Magnetic Field	B [T]	5	4.75	5.5
Rot. Transform	ι	0.95	0.95	0.95
Equiv. Current	I [MA]	3.68	3.50	3.85

The various options in Table 1 differ by the magnetic field strength, the reference case is HSR22B. In the following paper the issues of confinement, power balance and ignition are investigated. One of the main features of a Helias configuration is the reduced radial drift of charged particles, which leads to a reduced neoclassical transport of the thermal plasma. However, this also affects the α-particle confinement, where prompt losses of highly energetic α-particles can be reduced to a tolerable level and the reduction of α-particle heating can be kept below 5%. As shown by Lotz et al.[1] confinement of trapped α-particles depends on plasma beta, since with rising plasma pressure the poloidal drift of these particles is increased leading to their better confinement. Without this finite beta effect nearly all trapped α-particles would be lost to the wall before transmitting their energy to the background plasma. Ripple-trapped α-particles have been investigated in [2], where it was found that 10 coils per field period is the lower limit in order to avoid a large fraction of prompt losses by particles trapped in the modular coil ripple.

The accumulation of helium ash in HSR has not yet been considered in detail, although some qualitative statements are possible. On the positive side, neoclassical losses of trapped α-particles are predicted to be considerably larger in a Helias reactor than in an axisymmetric device and to have a much more favourable energy dependence (i.e. the loss rate increases rapidly as the α−particles give up energy to the bulk plasma). On the other hand, the large negative (ion-root) electric fields expected from the ambipolarity condition on the bulk plasma would favour accumulation of slow α-particles. For present purposes the amount of helium ash is considered to be a free parameter, allowing one to determine the maximum level tolerable under a given set of assumptions. The fraction of thermal α-

particles is expected to be 5 - 10%; in the following example f_α = 5% is assumed, however the effect of higher α-particle content is also analysed.

Anomalous transport in the Helias reactor is difficult to predict, since present scaling laws are obtained in magnetic fields with topologies different from that in a Helias reactor. Recently, based on experimental results from various stellarators and torsatrons, new stellarator scaling laws have been derived from the international stellarator data base (ISS) [3]. These results are listed in the following table 2 (ISS95 and ISS_{W7}). The scaling law ISS_{W7} is derived from Wendelstein 7-AS and Wendelstein 7-A data only. The general form the energy confinement time is a power law

$$\tau_E = \mathrm{Const.}\ R^{a1} a^{a2} B^{a3} <n>\_L^{a4} P^{a5} \kappa^{a6} \iota^{a7} A^{a8}$$

with major radius R, minor plasma radius a, magnetic field B, heating power P, elongation of magnetic surfaces κ (unity in stellarators), effective atomic mass A, line averaged density <n>_L, rotational transform ι. The Scaling with isotope factor A has not yet been confirmed in stellarators; here this factor may be used in order to test the sensitivity to parameter changes.

2. NEOCLASSICAL CONFINEMENT

Neoclassical transport in Helias has been investigated using Monte Carlo simulations [4], a numerical solution of the drift kinetic equation [5], and a combination of analytical and numerical solutions of the ripple-averaged kinetic equation [6]. All of these approaches have confirmed the significant reduction of neoclassical transport coefficients made possible by the Helias concept. These investigations have also confirmed the expected scalings of the mono-energetic transport coefficients with collision frequency and radial electric field, allowing a very efficient description of the results by a relatively simple analytic fit [7]. This fit has been incorporated into a stellarator-specific version of the 1-D transport code ASTRA [8], which has been used to simulate the start-up phase of the Helias reactor [9]; results indicate that neoclassical transport is sufficiently small to pose no barrier to ignition.

In all these calculations the radial electric field, determined from the ambipolarity condition on the particle fluxes, plays an important role in reducing the ion transport but has very little effect on electrons, which are predominantly in the "$1/\nu$ regime" (where transport coefficients are inversely proportional to collision frequency and independent of the radial electric field). This "ion root" mode of operation is only possible due to the strong reduction of $1/\nu$ losses inherent in the Helias concept. Thermal stability of the reactor is assured due to the strong scaling of the $1/\nu$ transport coefficients with plasma temperature $\chi_e \sim T^{7/2}$. The effects of finite plasma pressure, although critical to the effective confinement of highly energetic particles (Ref. [1]), are of relatively minor importance for the thermal transport coefficients of the the plasma in Helias reactors.

3. ANOMALOUS CONFINEMENT AND IGNITION CONDITIONS

In the following, plasma parameters in a Helias reactor will be calculated on the basis of empirical scaling laws. Several scaling laws of energy confinement time have been proposed. These are: Lackner-Gottardi scaling (LGS)[10], the gyro-Bohm (GRB) scaling and the LHD scaling (LHD).

Table 2: Exponents of empirical scaling laws

	LGS	ISS95	ISS_{W7}	LHD	GRB
Const	0.175	0.256	0.36	0.17	0.25
P a5	-0.6	-0.59	-0.54	-0.58	-0.68
R a1	1	0.65	0.74	0.75	0.6
a a2	2	2.21	2.21	2.0	2.4
B a3	0.8	0.83	0.73	0.84	0.8
ι a7	0.4	0.4	0.43	0.0	0.0
<n> a4	0.6	0.51	0.5	0.69	0.6

LHD-scaling and Gyro-Bohm scaling do not depend on the rotational transform, however the experimental data of Wendelstein 7-AS indicate an ι–dependence and therefore support the Lackner-Gottardi scaling law in this respect.

In extrapolating these scaling laws to a stellarator reactor the proper choice of the scaling law is of great importance. The ISS95 is based on data of all stellarators, its database is the largest, however it does not distinguish between low shear and high shear devices. The experimental results, however, show that there is a difference between these two categories. The experimentally obtained confinement times in Wendelstein 7-AS are larger than those predicted by the International Stellarator Scaling.

The energy confinement times in W 7-AS and W 7-A are roughly 25% larger than predicted by the ISS95 law. Since the major radius in these two devices is the same, scaling with major radius is undetermined. The choice here is to use the same exponent as in LHD scaling, however it has been analysed how the results of the extrapolation depend on this coefficient.

The Helias reactor is more closely related to low shear-configurations such as Wendelstein 7-A and Wendelstein 7-AS than to high-shear devices. Therefore extrapolating confinement times on the basis of LGS or ISS_{W7} scaling may be more appropriate than using those from the ISS95 scaling. The expected confinement times in the Helias reactor are about 1 ÷ 2 s, the highest confinement times are given by LGS and W7-scaling. Scaling laws like ISS95 predict a confinement time of 1 s, LG scaling and ISS_{W7} confinement times around 2 s. As will be shown in the following analysis a confinement time of 1 s is too short to reach ignition. The required value is around 1.8 s. The effective heating power is the alpha-particle power minus the Bremsstrahlung losses. Under reactor conditions the effective heating power is in the range from 300 to 700 MW.

The scaling laws described above have been used to test ignition scenarios in the Helias reactor. The procedure is as follows: After modelling the density and temperature profiles of a reactor grade plasma all relevant parameters are computed to test the power balance. The required confinement time to sustain the ignited plasma is compared with the confinement time computed from scaling laws. The following table displays the main plasma parameters of the reference reactor HSR22B

Table 3 Device data and plasma data of HSR22B

Major Radius	22	[m]	Z_{eff}	1.181	[]
Minor Radius	1.8	[m]	DT-Power Dens.(0)	2.66	[MW m^{-3}]
Elongation	1.0	[]	DT-Power	608	[MW]
Iota(0)	1	[]	Neutron Power	2434	[MW]
Equiv.Current	3.5	[MA]	Neutron Yield	$1.1x10^{21}$	[s^{-1}]
Toroidal. Current	0	[MA]	Tritium Rate	476	[g/d]
Equiv. Iota	0	[]	Deuterium Rate	311	[g/d]
Plasma Volume	1407	[m^3]	N-Power to F.W.	1.04	[MWm^{-2}]
Magnetic Field	4.75	[T]	Bremsstr. (0)	0.28	[MW m^{-3}]
Plasma Surface	1563	[m^2]	Bremsstrahlung	123	[MW]
El. Density n(0)	$3.43x10^{20}$	[m^{-3}]	Fusion Power	3044	[MW]
El. Density <n>_L	$2.4 x10^{20}$	[m^{-3}]	Net Heating Power	487	[MW]
El. Density <n>	$1.77x10^{20}$	[m^{-3}]	Conf. Time τ_E	1.72	[s]
Number of Electrons	$2.5 x10^{23}$	[]	α-Conf. Time	20.2	[s]
El. Temperature T(0)	14	[keV]	τ_E (LHD)	1.02	[s]
Av. El. Temperature	4.63	[keV]	τ_E (LGS)	1.79	[s]
H-Temperature T(0)	14	[keV]	τ_E (ISS_{W7})	2.24	[s]
H-Density $n_H(0)$	$1x10^{18}$	[m^{-3}]	τ_E (ISS)	1.03	[s]
D-Density $n_D(0)$	$1.4x10^{20}$	[m^{-3}]	τ_E (EH92y)	2.11	[s]
Number of Deuterons	$1.02x10^{23}$	[]	$N_D \tau_E$	$4.8x10^{20}$	[sm^{-3}]
T-Density $n_T(0)$	$1.4x10^{20}$	[m^{-3}]	$N_D T(0)\tau_E$	$6.75x10^{21}$	[m^{-3}keVs]
Number of Tritons	$1.02x10^{23}$	[]	Beta(0)	16.4	[%]
He-Density n(0)	$3x10^{19}$	[m^{-3}]	Av. Beta	4.43	[%]
Number of He atoms	$1.18x10^{22}$	[]	Plasma Energy	839	[MJ]
α-Fraction n_{He}/n_e	8.75	[%]	<Temperature>	5.18	[keV]

4. SUMMARY

Evaluating empirical scaling laws of stellarator experiments allows one to investigate ignition conditions of a Helias reactor. It is assumed that all α- particle power is available for plasma heating. This is justified by numerical calculations of particle orbits in the finite-ß magnetic field. In case of 10 coils per field period the modular ripple losses of alpha particles is negligibly small. The scaling law ISS95 predicts a confinement time which is too short to reach ignition; an improvement factor of two is needed. However, following LG scaling or $\mathrm{ISS_{W7}}$ (which is derived from the Wendelstein 7-A and Wendelstein 7-AS experiments only) ignition can be reached. These scaling laws do not invoke an isotope factor as has been found in tokamak experiments. Although LGS is derived for L-mode confinement in tokamaks it is sufficient for ignition in the Helias reactor. The reason is mainly the dependence on density ($\tau_E \sim n^{0.6}$) and the dependence on the rotational transform ($\tau_E \sim \iota^{0.4}$). High rotational transform in the Helias reactor improves the confinement and since there is no disruptive density limit in stellarators the scaling with density leads to an increase of confinement times. Furthermore, the tokamak scaling laws applied to the Helias reactor also yield ignition (Elmy-H and H-mode scaling). Table 3 includes the Elmy-H-mode scaling where the toroidal current is replaced by the equivalent current of 3.5 MA, which corresponds to the rotational transform $\iota = 1$. The operational regime envisaged is below the expected stability limit of $\langle\beta\rangle = 5\%$; the fusion power output is about 3500 MW. The present analysis shows that the empirical scaling laws of the Wendelstein stellarators are compatible with the requirements of a stellarator reactor. However, the distance in parameter space between present stellarator experiments and the Helias reactor is rather large. Therefore, one might argue that error bars of the predicted confinement times are too big to allow for reliable extrapolations towards the reactor. In the paper of Stroth et al. (ref. [3]) L-mode data of tokamaks and stellarator data are plotted against the ISS95 which also shows the strong similarity of stellarator confinement and tokamak L-mode confinement. Therefore one may expect that the error bars in predicting confinement times is a Helias reactor are smaller than those based on stellarator experiments only.

Extrapolation towards the reactor regime necessarily means going beyond the limits of the parameter regime where the scaling laws have been established. In particular this affects the scaling with density. In the reactor, the assumed density is roughly a factor of two larger than in the ISS95 data set; the line averaged density in the Helias reactor is $2.4\mathrm{x}10^{20}\ \mathrm{m}^{-3}$. However, the density limit in stellarators is mainly caused by impurity radiation and therefore depends on wall conditioning and impurity control, which indicates the uncertainty in density scaling of τ_E. Ignition at lower densities than envisaged in the standard case is still possible if confinement is determined by the scaling law $\mathrm{ISS_{W7}}$ or the tokamak Elmy-H-mode scaling. The plasma parameters are $T(0)$ = 19 keV and $\langle n\rangle\_L$ = $1.5\ \mathrm{x}10^{20}\ \mathrm{m}^{-3}$, which are close to those envisaged for ITER. Furthermore the dependence on rotational transform goes beyond the present parameter regime. In the regime $\iota \leq 0.5$ the positive scaling of τ_E with ι is established experimentally, however in the Helias reactor ι is equal to unity which is a factor of two larger than in Wendelstein 7-AS. In future large-scale experiments (Wendelstein 7-X and LHD) will appreciably improve the experimental data base of stellarator confinement and will lead to a better prediction of the reactor confinement times.

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